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Prescribed fire experiences on crop residue removal for biomass exploitations. Application to the maritime pine forests in the Mediterranean Basin

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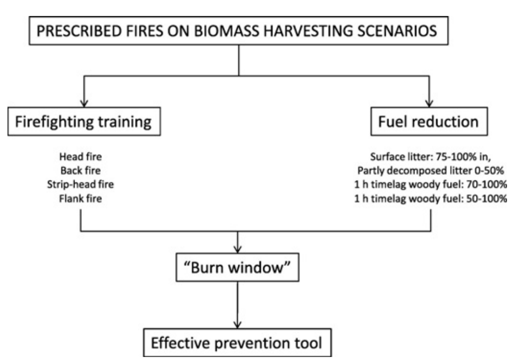
HIGHLIGHTS

- Large quantities of coarse woody debris were found after biomass harvesting scenarios.
- Prescribed fires under these conditions could fulfill a meaningful fire prevention function.
- Partly decomposed litter moisture plays an essential role in fuel reduction.
- Prescribed fires can be an efficient and valuable tool according to the "burn window".

GRAPHICAL ABSTRACT



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ABSTRACT

Socioeconomic changes, climate change, rural migration and fire exclusion have led to a high woody biomass accumulation increasing potential wildfire severity. Mechanical thinning and prescribed burning practices are commonly used to prevent large fires. The purpose of this study was to assess burning treatment effectiveness following mechanical thinning from biomass harvesting. Prescribed burning to reduce residue removal could help mitigate fire behavior, mainly in strategic management or critical focal points.

Field samplings were conducted before and immediately after burnings on different environmental scenarios where fuel load was classified by categories. Prescribed fires reduced available fuel in all fuel categories, mainly in surface litter layer. Total fuel load reduction ranged from 59.07% to 86.18%. In this sense, fuel reduction effects were more pronounced when burns were conducted fewer than 10% on surface litter moisture. The difference in fuel consumption among scenarios was higher for most all woody fuel components and decomposition litter layer than for surface litter layer. Managers can use this information to design technical prescription to achieve the targets while decomposed litter retention maintaining the soil properties and biodiversity. Understanding the most effective "burn window" should help better plan prescribed burning, both in term of fire behavior and fuel consumption, without altering ecosystem properties.

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1. Introduction

Large wildfires are a societal problem that affects millions of hectares around the world, causing huge ecological and economic impacts (Rodríguez y Silva and González-Cabán, 2010). Although fire has played a keystone role in the configuration of Mediterranean landscapes, recent socioeconomic and climate changes have increase fire severity and large fire occurrence (Cardil et al., 2014). One of the main causes of fire severity is the abandonment of forest activities because of its low profitability, and as a consequence, a large accumulation of both live and dead biomass (Molina et al., 2011). In this sense, biomass harvesting for energy could hold an important key to future economic development for Mediterranean forests (Madrigal et al., 2016).

Landscape-level fuel treatments strategically allocated in time and space can be combined with forest management efforts to reduce extent and severity of forest fires (Agee and Skinner, 2005). Mechanical thinning can alter stand structure providing benefits on crown fire behavior (Cruz et al., 2006), in spite of the increase of coarse woody fuel from harvesting operations and dead and down woody fuel beneath a forest canopy. Thinned forests are typically open and heterogeneous at small spatial scales, formatting mosaics of canopy gaps and tree clusters variable in size and shape (Lydersen et al., 2013). These gaps provide an increment of the wind speed based on a reduction of drag coefficient. Therefore, reliance on thinning alone to wildfire prevention is not possible in all environmental scenarios and forest structures (Molina, 2015). Prescribed fire treatments can reduce surface fuels, mainly residue load are generated by biomass harvesting (Harrod et al., 2009). However, research of its potential effects on forest ecosystems and their accompanying services is still required, adding uncertainty (Valor et al., 2015). The estimation of fuel consumption is a recommended procedure in prescribed fire planning (Fernandes and Loureiro, 2013).

Creating fire-resistant forests through fuel treatments such as thinning and prescribed fires would be benefit from the safety, efficiency and effectiveness of fire suppression (McCaw, 2013). The effectiveness of a prescribed fire may be obscured by many factors, including forest structure, forest type, fuel moisture, fire weather and ignition patterns (Van Mantgem et al., 2016). In this sense, while prescribed fire is expected to reduce surface fuels, it is possible that coarse woody fuel may be high from branch and brooms fall from heating or scorch pruning (Agee and Lolley, 2006). Furthermore, residual woody debris are an important legacy of harvesting operations that create a new artificial fuel model with a greater fuel load than conventional litter fuel models (Molina, 2015). The heat released by consumption of heavy residual fuels may cause torching of nearby trees and long-distance spot fires (Knapp et al., 2005).

Prescribed burning is a commonly used method to fuel reduction, but it must be balanced with organic layers retention to maintain soil properties and other forest functions (Fernandes and Loureiro, 2013). While prescribe fires that consume little fuel may not be adequately reduce fire risk, the excessive loss of organic matter may lead to erosion and reduced abundance and diversity of fire sensitive species (Dahlberg et al., 2001). But the duff and woody debris found in many harvesting operations can result in long residence times. The duff layer is typically consumed through smoldering combustion after the flaming front has passed generating a considerable amount of heat (Knapp et al., 2005). The amount of fuel consumed by categories can be controlled by "burn window" or varying the fuel moisture and weather conditions that burns were conducted (Valor et al., 2015). Achieving an optimal "burn window" or effective burn conditions can be particularly challenging when residual load is high and compacted.

This work presents the results of combinations of mechanical thinning (biomass harvesting) and burning treatments in Maritime pine (*Pinus pinaster* Aiton), which is a conifer from the western Mediterranean Basin with a distribution that exceeds 4 millions ha under different origins and environmental conditions (Fernandes and Rigolot, 2007). The aim of this study was to assess the effects of prescribed fires on residue removal for biomass harvesting exploitation based on pre-fire and post-fire field samplings. To estimate the practical effectiveness, we quantified the fuel consumption according to the different litter layers and woody fuel categories taking into account partly decomposed litter consumption under 50% to soil erosion mitigation. Later, fuel moisture and weather conditions were identified by the fourteen burning scenarios (period 2014–2016) in order to estimate the most effective "burn window". The knowledge of Rx window could become essential for integrated fire management planning and budget allocation in fuel treatment optimization to mitigate the transition between surface fire and crown fire and fire ecological and socioeconomic impacts.

2. Material and methods

2.1. Study area

Pinus pinaster forests play an important role in the province of Ciudad Real, located in southern of Spain, occupying an area about 42,000 ha. The province of Ciudad Real is characterized by a Mediterranean climate with a pronounced dry period a daytime summer temperatures above 35 °C. The fire occurrence is a serious problem with official statistics indicating an average of 116.5(±32.04) fires per year and an affected forest area of 765.69(±498.07) hectares (period 2006–2015). The study was conducted in the "Puebla de Don Rodrigo" and "Viso del Marqués" forests, all of public domain (Fig. 1). The study area is located between UTM coordinates of (371,600; 4,330,000) and (463,300; 4,251,000). While in "Puebla de Don Rodrigo", the average slope ranges from 10% to 20%, in "Viso del Marques" varies between 15 and 30% showing preference to exposures in the north and northeast. Canopy associations include some small clusters of *Quercus ilex* and *Q. faginea*. The fuelbed is composed of long-needle pine litter with some both fine and coarse fuels. In the canopy gaps, the understory is dominated by *Cistus* spp. and *Rosmarinus officinalis*.

These forests have been managed from the viewpoint of forest biomass harvesting according to periodic thinning operations. Prescribed fire planning (2014–2016 period) included two public domain lands, Puebla de Rodrigo (PR) and Tolmo (T), with the following objectives: firefighting training, sustainable forest management and forest fire prevention. To achieve these objectives, mechanical selected thinning followed by prescribed fire was tested in combination. A feller-buncher, a cable skidder and a forwarder were used to harvesting operations using full tree method. The study was undertaken in six *P. pinaster* stands that cover >42 ha. The treatments included: control forest with thinning and pruning made in 2006–2007 ("PR1"), heavy thinning followed by prescribed fire ("PR2") and moderate thinning followed by prescribed fire ("T1", "T2", "T3" and "T4"). In spite of the high biomass extraction of "PR2", skidding was not necessary because of the low slope and accessibility to forwarding. When logging operations did not take into account the skidding, the crop residue load to the ground was reduced based on the lack of which actions during the extraction operations. Finally, fire management agency removed the important load of crop residues on different stands involved in biomass harvesting using prescribed fire.

2.2. Stand characterization

The data sampling collected both environmental information and stand variables to assess biomass harvesting. Based on a maximum sampling error of 30% with a fiducial probability of 95% and using statistical variable stand density, we calculated the number of plots for each stand according to a proportional allocation. The forest inventory was carried out in circular plots of 1000 m^2 across the different stands incorporating variables such as stand density, diameter at breast height, stand height, basal area and estimated biomass harvesting. Analysis of variance (ANOVA) was used to determinate if significant differences ($p < 0.05$)

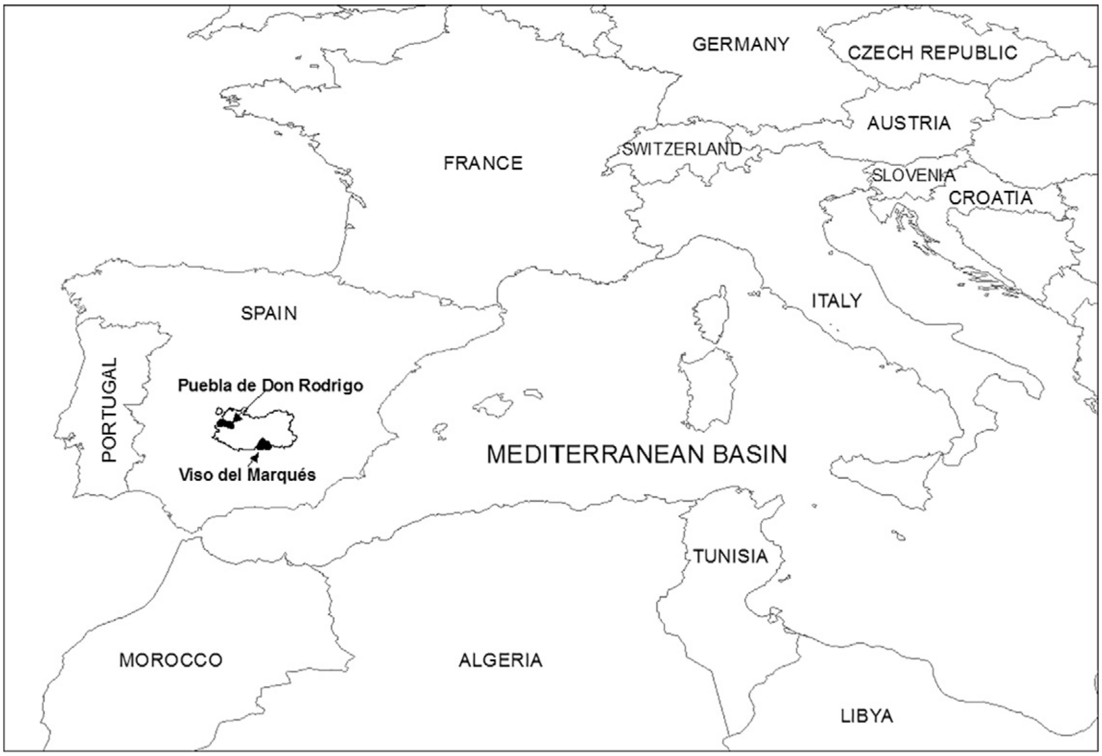

Fig. 1. Study area location.

existed in stand density, diameter at breast height, stand height, basal area and biomass harvesting for each study stand. SPSS$^{(C)}$ was used in all analysis. If significant differences were detected, a Tukey HSD test was performed to determine which specific stand was different from another.

2.3. Surface fuel characterization

The characterization of surface fuel was conducted though destructive transects using the line-intercept method (Stephens and Moghaddas, 2005). Field samplings were carried out from one day before to a few hours before burning treatment to obtain a better modeling of the burned areas. Line transects and 4 clipped vegetation plots were located in each experimental plot. Along with vegetation composition, UTM coordinates; fuelbed depth, spatial distribution and vertical structure were also identified at each plot. At the same time, a photographic overview was taken as a visual key to recognize the different fuel models. Fuel models proposed by Rodríguez y Silva and Molina (2012) are used due to the need for more fuel model options to select from litter and dead woody fuel beneath a forest canopy ("fuel model 9" according to traditional fuel modeling).

Fuel load was determined in sampling plots with areas of 100 × 100 cm showing fuel load by category (live and dead) and particle size (expressed in 1-. 10-, 100-h time-lag). Once all the samples were collected, and prior to their statistical analyses, the moisture content for each sample was estimate in order to represent fuel load as dry matter content. Similar to other studies (Rodríguez y Silva and Molina, 2012), separate live and dead fuel by particle size was needed to identify fuel moisture. Each sample underwent a 72-hour drying process in an oven set at 60 °C (Hernando, 2009), at which this time, fuel weights were constant. Fuel load was converted to dry fuel after the percentage of moisture was eliminated. Similar to stand characterization, ANOVA analysis and Tukey HSD test were performed to identify if significant differences ($p < 0.05$) existed in total fuel, fuel load by categories and fuelbed depth.

2.4. Fire behavior

The fire spread analysis was conducted in 14 plots with 20 m wide and 30 m long. Two anemometers were placed around each plot to identify meteorological parameters. Prior to the burn, 30 temperature probes (thermocouple type k) with 50 μm wire diameter were placed inside the litter layer. The data loggers were programmed to capture air temperatures every second on the day of the burn. From these data, we could obtain: spread rate, maximum temperature, time of maximum temperature and flame residence time or duration of temperature above 285 °C.

Two video cameras and an infrared camera were also used to determinate suitably the fire spread and flame length. Flame length could be indirectly identified from the flame height and flame angle (the angle formed between the flame front and the un-burned fuel bed:

$$L = H/\sin A$$

where "L" is the flame length (m), "H" is the flame height (m) and "A" is the flame angle (°).

Fire intensity, expressed as kilowatts per meter, is determined by the following equation according to the available fuel and spread rate:

$$I = (18,500 * AF * SR)/60$$

where "I" is the fire-line intensity (kW/m), "AF" is the available fuel load (kg/m^2) and "SR" is the spread rate (m/min). A basic value of 18,500 kJ/kg can be used for the low heat of combustion (Albini, 1976). The units of fire intensity should be converted to kilowatts per meter using a division into 60 s.

Heat per unit area is calculated as the product between available fuel load and the gross calorific value by the following equation:

$$H = 4,500 * AF$$

where "I" is the heat per unit area (kcal/m^2), "AF" is the available fuel

load (kg/m^2) and 4500 (kcal/kg) is the average gross calorific value of Mediterranean species (Hernando, 2009).

Multiple regression analysis (linear, logarithmic, polynomial, power and exponential) was used to develop fire behavior equations to predicting spread rate and fire-line intensity from field inventories variables. In some cases, a Principal Component Analysis (PCA) allowed us to reduce a smaller and conceptually more coherent set of variables.

2.5. Fuel consumption

We proposed a destructive post-fire inventory to determinate fuel load consumed from fire. Fuel consumption was estimated using destructive sampling of 4 clipped burned plots in each experimental scenario. Fuel residue was separated into particle size and weighted immediately after burning. Sub-samples of each time-lag category were oven-dried for moisture content determination, similar to the pre-fire inventory. Fuel consumption was determined according to the fuel load differences between pre- and post-fire samplings. The availability of fuel is not homogeneous for each fraction, and therefore, each of them should be separately identified by the destructive sampling. Finally, fuel reduction per plot was obtained by adding the available biomass of surface litter or "L layer" (needle's biomass by the percentage consumed), available biomass of partly decomposing but still recognizable litter or "F layer" (litter biomass by the percentage consumed), 1-h timelag available fuel (woody coarse debris by the percentage consumed) and 10-h timelag available fuel (woody coarse debris by the percentage consumed).

Analysis of variance (ANOVA) was used to determinate if significant differences ($p < 0.05$) existed in fuel consumption. A multiple analysis was developed for predicting fuel load reduction of each biomass fraction from moisture contents and fire behavior parameters. Observation of the absolute estimation error and significance level was considered in choosing the best functional form.

3. Results

3.1. Fuel characterization

The most of the stands were exploited in 2014, except in the case of "PR2", which was made in 2013. Control stand ("PR1") showed differences in stand density and basal area when compared with the rest of stands (Table 1). Although diameter at breast height was significantly lower in "PR" stands than in "T" stands, basal area was more variable ranging from 9.12 to 41.87 m^2/ha (Table 1). In relation to biomass harvesting, "PR2" can be pointed out as the heaviest exploitation.

The surface fuel was dominated by needles with dead woody fuel beneath a biomass harvesting treatment. In the cases of "PR1" and "T4", there was live fuel which slightly affected fire behavior. Fine dead fuel (1-h timelag) identified three groups: low ("PR2"), moderate ("PR1" and "T3") and high ("T1", "T2" and "T4") (Table 2). Dead fuel 10-h timelag was significantly increased in the "T4", "T2" and "T3". This former stand stood out above dead fuel 100- h timelag and depth. The total fuel load was high, exceeding 10 t/ha, in all stands except "PR2". Fuel load was significantly increased in the "T" stands when compared with the "PR" stands (Table 2). According to fuel characterization, we could identify four fuel models (Rodríguez y Silva and Molina, 2012): "HR5", "HR7", "HR8" and "R1". All of the stands were characterized by "HR" fuel group, except in the case of "T3" due to its 10- and 100-h timelag loads.

3.2. Fire behavior

The moisture content, both surface and partly decomposed litter layers, varied based on each stand, showing differences on the fire spread. "T" scenarios showed much drier conditions than "PR" scenarios, mainly in "T1" and "T2" stands. According to statistical analysis, while surface moisture content identified two significant groups, partly decomposed litter content showed three groups (Table 3). The moisture of this former layer tented to decrease from "PR1", "T1" and "T2" stands according to meteorological conditions that affected the Mediterranean Basin in the previous days. However, there was a great difference between "PR1" and "PR2" decomposed litter moisture in spite of their similar meteorological conditions.

The wind speed was taken from the two anemometers, located at the both sides of each burn, which was not influenced by the fire and the smoke. In spite of the variation of wind speed, mainly due to the gusts of wind, showed impacts on fire spread parameters, the higher differences on fire parameters were identified by the integration among the type of conduction, the wind speed and the fuel moisture. There were significant differences for fire behavior according to burning technique ("T4" stand was a representative example). The first parameter, fire spread, identified four significant groups (Table 4), highlighting the "T4-1" scenario, fairly followed by the "T1-3" and "T3-3" scenarios.

Flame length was <1 m in all scenarios, although "T2" scenarios and "T3-1" scenario surpassed the rest (Fig. 2). Fire-line intensity identified five significant groups: very low ("PR1-3", "PR2-1", "T4-3"), low ("PR1-1", "PR1-2", "T1-2", "T2-1", "T2-2", "T4-2"), medium ("T1-1", "T2-3"), moderate ("T1-3", "T3-1") and high ("T4-1") (Table 4). In relation to heat per unit area, "T" stands can be pointed out as more virulent events than "PR" burns. Mean maximum temperature was not statistically different among plots, although "PR1-2" reached the maximum mean temperature. Residence time was increased in "T1" and "T2" scenarios compared with the rest of prescribed fire techniques. With similar environmental and fuel conditions, residence time was increased in backfire in relation to head fire ("PR1-3" and "PR1-1", "T4-3" and "T4-2").

Exponential form showed more reliable adjusts than the rest of functional forms (Eq. (1)) based on the statistical criteria (estimation error, determination coefficient and $p < 0.05$) and PCA analysis. This equation obtained an absolute error estimation of 0.18($\pm$0.18) m/s using only four variables according to PCA results (it is possible to explain 92.6% of the total spread rate variance with only four components). On the other hand, fire-line intensity was fitted by logarithmic form showing

Table 1
Characterization of vegetation structure for each stand.

Stand	PR1	PR2	T1	T2	T3	T4
Date	29/04/2014 and 30/04/2014	29/04/2014	22/04/2015	23/04/2015	27/04/2016	28/04/2016
Area (ha)	4,75	2,75	15,38	1,62	4,07	14,37
Slope (%)	<10	10–20	15–30	15–30	15–30	15–30
Aspect	North/South	North	North	Northeast	North/Northeast	Northeast
Stand density (trees/ha)	1209,58 ($\pm$141,42)^a	354,27 ($\pm$75,66)^b	253,43 ($\pm$12,06)^b	331,08 ($\pm$65,77)^b	403,5 ($\pm$46,41)^b	469,13 ($\pm$34,92)^b
Diameter at breast height (cm)	21($\pm$1,35)^a	18,11($\pm$1,96)^a	30,01($\pm$6,06)^b	27,59($\pm$1,98)^b	27,5($\pm$0,25)^b	27,2($\pm$0,2)^b
Stand height (m)	14,10($\pm$0,36)^a	14,60($\pm$0,71)^a	12,08($\pm$1,62)^a	10,62($\pm$1,59)^a	9,23($\pm$0,3)^a	9,12($\pm$0,78)^a
Basal area (m^2/ha)	41,87($\pm$14,56)^a	9,12($\pm$5,58)^b	20,67($\pm$3,81)^c	25,44($\pm$3,71)^c	21,20($\pm$0,54)^c	27,27($\pm$3,44)^c
Biomass harvesting (t/ha)	0	31,57($\pm$24,67)^a	15,34($\pm$0,45)^b	15,34($\pm$0,45)^b	14,7($\pm$0,35)^b	14,7($\pm$0,35)^b
Biomass harvesting (year)	–	2013	2014	2014	2014	2014

The term in brackets is the standard deviation of the sample.
Mean values in a row followed by the same letter are not significantly different ($p < 0.05$).

Table 2
Characterization of fuel model for each stand.

Stand	PR1*	PR2	T1	T2	T3	T4*
Dead fuel 1 h (t/ha)	11.30(±3.18)[a]	5.02(±4.12)[b]	14.81(±4.58)[c]	16.04(±1.16)[c]	8.93(±1.36)[a]	20.46(±1.56)[c]
Dead fuel 10 h (t/ha)	1.01(±0.84)[a]	1.65(±0.29)[a]	4.95(±4.18)[b]	7.44(±3.37)[b]	12.21(±2.12)[c]	3.57(±2.81)[b]
Dead fuel 100 h (t/ha)	0.79(±1.36)[a]	3.20(±2.89)[b]	4.42(±3.69)[b]	4.79(±4.70)[b]	6.02(±3.23)[c]	1.63(±1.44)[b]
Live fuel 1- and 10-h timelag (t/ha)	–	–	–	–	2.1(±0.72)	–
Total fuel (t/ha)	13.10(±3.04)[a]	9.87(±8.71)[a]	24.18(±10.29)[b]	23.81(±11.53)[b]	29.26(±3.99)[b]	27.65(±2.81)[b]
Depth (cm)	4.49(±1.69)[a]	5.66(±4.60)[a]	5.7(±2.54)[a]	5.93(±2.87)[a]	20.29(±28.87)[b]	4.5(±0.78)[a]
Fuel model (Anderson, 1982)	9	9	9/11	9/11	11	9/11
Fuel model (Rodríguez y Silva and Molina, 2012)	HR5	HR7	HR8	HR8	R1	HR8

The term in brackets is the standard deviation of the sample.
Mean values in a row followed by the same letter are not significantly different ($p < 0.05$).
* Existence of live fuel which slightly affects fire behavior.

an absolute error estimation of 116.73(±67.39) kW/m (Eq. (2)).

$$v = 1.028\ \exp(0.066 * W + 0.062 * D - 0.061 * Md + 0.13 * Ml) \quad R^2 = 0.88 \tag{1}$$

$$I = 795.82 * \ln(L) + 1,553.69 \quad R^2 = 0.92 \tag{2}$$

where “v” is the spread rate (m/min), “W” is the mean maximum wind speed (km/h), “D” is the fuelbed depth (cm), “Md” is the decomposed litter moisture (%), “Ml” is the surface litter moisture (%), “I” is the fire-line intensity (kW/m) and “L” is the flame length (m).

3.3. Fuel consumption

The surface litter reduction was similar for all stands varying between 88.98% and 99.5% (Table 5). The decomposed fuel reduction was increased in the 2015 burnings (“T1” and “T2”). On the other hand, “T4” treatment was pointed out as the less effective burning. In the same year, 1-h timelag fuel reduction ranged from 46.68% (“PR2”) to 96.26% (“PR1”) (Table 5). In the 10-h timelag fuel consumption, the only significant difference was between “T2” and “T4” stands and the rest of them. Total fuel reduction identified three significant groups: low consumption (“PR2”, “T3” and “T4”), moderate consumption (“PR1” and “T1”) and high consumption (“T2”).

There was a negative correlation between surface litter moisture and total fuel consumption ($r = -0.751$, $p < 0.1$). The maximum fuel consumption, for both litter layers (“L” and “F” litter layers), were provided in higher residence times ($r = 0.814$, $p < 0.05$). Partly decomposed litter moisture was the necessary variable to explain the fuel reduction in the upper litter layer and coarse woody fuel ($r > 0.85$). From a statistical point of view, decomposed litter moisture, spread rate and fuel consumption of surface litter layer were the most suitable variables for estimating fuel reduction (Table 6). Therefore, decomposed litter reduction was identified by surface litter consumption showing a meaningful fit.

4. Discussion

Fire behavior measures allow us to compare prescribed fires in order to a much exacter practice than only visual estimation (Morandini et al., 2006). An average estimation of each burning can contribute useful because of the spatial distribution of fuel model and weather conditions, and as a consequence, the fire spread varies in time and space (Van Mantgem et al., 2016). In this sense, the variability in each stand was accounted by estimating the standard deviation of each parameter. The scale of the experimental plots (500 m2) might be interpreted as an undervaluation of fire behavior, mainly in spread rate. However, the plot size was designed based on a length of maximum run using strip-head fire, which is the most useful technique to prescribed fires on canopy fuel models (Stephens and Moghaddas, 2005; Hiers et al., 2009).

The surface litter moisture ranged from 8.28% to 14.78% including past weather conditions (Table 3). Furthermore, other factors could contribute to the moisture content detection at each stand, mainly the shading of surface models due to the smaller differences in topographic characteristics. In similar meteorological and shading conditions, “T4” tended to have more litter moisture than “T3”, and “T1” more than “T2” in relation to the higher fuelbed compaction. On the other hand, partly decomposed litter moisture varied from 23.03% to 44.92%. In this case, previous meteorological conditions played an important role under similar fuel model characterization (“T1 and T2” in comparison with “T3 and T4”).

Large quantities of coarse woody debris were found in the area similar to other studies (Harrod et al., 2009). We observed that a high removal of trees during biomass harvesting (“PR2” in relation to “PR1”)

Table 3
Characterization of environmental conditions for each scenario.

Scenario	Surface litter moisture (%)	Partly decomposed litter moisture (%)	Mean wind speed (km/h)	Mean maximum wind speed (km/h)	Type of fire conduction
PR1-1	14.78(±3.56)[a]	26.86(±0.20)[a]	2.96(±1.25)[a]	6.53(±1.15)[a]	Head fire
PR1-2	14.78(±3.56)[a]	26.86(±0.20)[a]	2.96(±1.25)[a]	6.53(±1.15)[a]	Flank fire
PR1-3	14.78(±3.56)[a]	26.86(±0.20)[a]	2.96(±1.25)[a]	6.53(±1.15)[a]	Back fire
PR2-1	14.78(±3.56)[a]	44.92(±12.70)[b]	2.91(±0.68)[a]	5.14(±0.84)[a]	Head fire
T1-1	9.1(±1.21)[b]	27.91(±6.90)[a]	9.23(±3.84)[b]	10.89(±3.69)[b]	Head fire
T1-2	9.1(±1.21)[b]	23.03(0.56)[a]	11.24(±6.08)[b]	10.32(±3.92)[b]	Head fire
T1-3	9.1(±1.21)[b]	23.03(0.56)[a]	11.16(±4.20)[b]	11.64(±6.48)[b]	Head fire
T2-1	8.28(±1.42)[b]	23.03(±0.56)[a]	0.74(±1.60)[c]	0.75(±1.80)[c]	Head fire
T2-2	8.28(±1.42)[b]	23.03(±0.56)[a]	1.61(±1.91)[c]	1.67(±2.21)[c]	Head fire
T2-3	8.28(±1.42)[b]	23.03(±0.56)[a]	3.58(±3.23)[a]	3.90(±3.96)[a]	Head fire
T3-1	11.4(±1.69)[a]	35.54(±7.99)[c]	5.50(±3.68)[a]	5.92(±4.91)[a]	Head fire
T4-1	12.26(±1.55)[a]	34.62(±6.09)[c]	3.05(±0.63)[a]	5.66(±1.91)[a]	Flank-Head fire
T4-2	12.26(±1.55)[a]	34.62(±6.09)[c]	3.05(±0.63)[a]	5.66(±1.91)[a]	Head fire
T4-3	12.26(±1.55)[a]	34.62(±6.09)[c]	3.05(±0.63)[a]	5.66(±1.91)[a]	Back fire

The term in brackets is the standard deviation of the sample.
Mean values in a column followed by the same letter are not significantly different ($p < 0.05$).

Table 4
Identification of fire spread parameters for each scenario.

Scenario	Spread rate (m/min)	Flame length (m)	Fire-line intensity (kW/m)	Heat per unit area (kcal/m^2)	Mean surface temperature (°C)	Mean residence time (s)
PR1-1	2.78(±1.25)[a]	0.42(±0.25)[a]	658.3(±134.56)[a]	3395.65(±646.16)[a]	672(±95.78)[a]	115(±43.52)[a]
PR1-2	1.56(±0.13)[a]	0.34(±0.10)[a]	422.79(±167.68)[a]	3540.89(±488.76)[a]	740.5(±153.76)[a]	172(±32.52)[b]
PR1-3	0.25(±0.03)[b]	0.16(±0.08)[b]	54.36(±18.27)[b]	3118.07(±1048.10)[a]	499(±243.95)[a]	134(±132.76)[a]
PR2-1	0.59(±0.03)[c]	0.25(±0.12)[b]	55.17(±17.32)[b]	1340.9(±420.99)[b]	670(±92.58)[a]	123(±93.41)[a]
T1-1	1.90(±0.14)[a]	0.7(±0.25)[c]	915.95(±21.95)[c]	7035.75(±168.65)[c]	602.5(±145.80)[a]	259.75(±124.06)[c]
T1-2	1.85(±0.28)[a]	0.45(±0.21)[a]	748.89(±129.88)[a]	6192(±1024.59)[c]	602.5(±145.80)[a]	259.75(±124.06)[c]
T1-3	2.67(±0.15)[d]	0.58(±0.24)[a]	1132.79(±187.44)[d]	6192(±1024.59)[c]	626.12(±174.84)[a]	253.33(±223.88)[c]
T2-1	0.75(±0.21)[c]	0.82(±0.18)[c]	361.56(±8.67)[a]	7035.75(±168.65)[c]	654.61(±159.62)[a]	270.44(±217.95)[c]
T2-2	1.12(±0.02)[a]	0.80(±0.42)[c]	593.97(±87.91)[a]	7740(±1145.51)[c]	671.57(±107.49)[a]	270.44(±217.95)[c]
T2-3	1.87(±0.01)[a]	0.81(±0.41)[c]	991.72(±146.77)[c]	7740(±1145.51)[c]	671.57(±107.49)[a]	168.71(±217.95)[b]
T3-1	2.65(±0.21)[d]	0.99(±0.29)[c]	1488.5(±263.75)[d]	7391.92(±768.44)[c]	628.75(±16.71)[a]	125(±49.5)[a]
T4-1	6.05(±1.62)[c]	0.65(±0.21)[a]	2273.5(±886.20)[e]	5678.55(±841.31)[d]	688(±27.91)[a]	28(±21)[d]
T4-2	1.45(±0.21)[a]	0.50(±0.14)[a]	541.14(±142.83)[a]	5183.1(±490.97)[d]	510(±120.01)[a]	72(±30.11)[a]
T4-3	0.2(±0.14)[c]	0.48(±0.16)[a]	77.5(±61.52)[b]	5059.24(±315.81)[d]	595.5(±28.02)[a]	144(±42.04)[b]

The term in brackets is the standard deviation of the sample.
Mean values in a column followed by the same letter are not significantly different ($p < 0.05$).

increased substantially the amount of 10- and 100-h timelag fuels similar to other stands (Agee and Lolley, 2006). Moreover, decomposed litter moisture was greater than before mechanical thinning and chipping. This fact could be in relation to the more compacted fuelbed generated from these harvesting operations. In all studied stands, the maximum temperature was found above 550 °C. The higher residence time in "T1" and "T2" stands may be related to the less moisture content for both surface and partly decomposed layers. In this sense, a significant correlation between residence time and surface litter moisture content was found ($r = 0.761$, $p < 0.1$).

The recorded information from the sensors located throughout the study stands allowed us to evaluate some aspects of fire behavior.

Fig. 2. Fire behavior scenarios using strip-head fire technique.

Table 5
Fuel consumption for each stand according to environmental conditions and fire behavior.

Stand	Surface litter reduction (%)	Partly decomposed litter reduction (%)	1-h timelag dead fuel reduction (%)	10-h timelag dead fuel reduction (%)	Total fuel reduction (%)
PR1	99.21(±1.01)[a]	41.83(±23.36)[a]	96.26(±4.89)[a]	72.64(±28.48)[a]	76.27(±37.16)[a]
PR2	88.98(±8.20)[b]	21.94(±8.59)[b]	46.68(±24.68)[b]	65.94(±37.30)[a]	61.01(±30.59)[b]
T1	98.9(±0.14)[a]	49.45(±31.80)[a]	90.41(±3.07)[a]	68.54(±33.99)[a]	78.28(±10.40)[a]
T2	99.5(±0.70)[a]	61.93(±33.75)[a]	78.64(±19.71)[c]	49.63(±37.55)[b]	86.18(±6.17)[c]
T3	98.1(±2.82)[a]	46.36(±40.01)[a]	78.5(±9.19)[c]	61(±7.07)[a]	59.07(±5.83)[b]
T4	82.5(±10.61)[b]	3.53(±3.5)[c]	77.5(±17.67)[c]	50(±16.97)[b]	63.5(±7.77)[b]

The term in brackets is the standard deviation of the sample.
Mean values in a column followed by the same letter are not significantly different ($p < 0.05$).

Flank-head fire showed the maximum spread rate based on the interaction between ignition lines. According to head fire spreads, differences could be observed on spread rate by the integration of wind speed, fuelbed depth and fuel moisture (Eq. (1)). Spread rate was not influenced by slope and aspect, contrasting with other conventional approaches (Rothermel, 1972; Finney, 1998). This fact could be in relation to the limited topographic characteristics among the studied stands. It would be necessary to increase the sampling size and topographical range to identify its role on the spread rate under prescribed fire conditions. As stated in the results, the most relevant factor in head fire spread was the wind velocity ($r = 0.598$, $p < 0.1$), mainly the gusts or the mean maximum speed. The compacted fuelbed depth also plays a meaningful performance on spread rate. In spite of traditional potential fit to fire intensity modeling (Byram, 1959; Alexander and Cruz, 2012), we selected logarithmic form to fire-line estimation based on coefficient of determination and estimation error ($R^2 = 0.92$ and estimation error = 116.73 kW/m). Potential form also showed an acceptable adjust ($R^2 = 0.84$ and estimation error = 287.47 kW/m).

Organic forest floor layers are important to soil stability and fertility and overall ecosystem integrity (Dahlberg et al., 2001; Fernandes and Loureiro, 2013). Hence, the importance of fuel consumption on the partly decomposed litter layer under 50% of its total depth. Partly decomposed litter moisture can be interpreted as an essential factor in total fuel reduction ($r = -0.883$, $p > 0.05$) and 1 h timelag fuel reduction ($r = -0.82$, $p < 0.05$). This only variable accounted for above 85% of the variance on total fuel and 1- and 10- h timelag fuels reduction. "Layer F" must have been influenced by the amount of surface litter had been consumed. With more available surface fuel, the fire-line is more virulent, and as a consequence, the down layer would be more consumed than in low-intensity fires (Hartford and Frandsen, 1992). In this sense, we have obtained a significant relationship between "Layer H" reduction and "Layer F" consumption ($r = 0.957$, $p < 0.05$).

In the study area, firefighting training and residual fuel reduction of biomass harvesting were identified as the most essential tasks. Prescribed fire is widely used forest management tool, yet the long-term effectiveness of prescribed fire in reducing fuels and fire hazards in many vegetation types is no well documented (Fernandes and Loureiro, 2013; Valor et al., 2015; Van Mantgem et al., 2016). Although there were differences among burning scenarios, post-fire reduction in surface fuels, mainly in fine dead fuel load, were known in all stands. Burning treatments should have resulted in a fuel reduction ranged from 75% to 100% in surface litter, from 0% to 50% in decomposition litter, from 70% to 100% in 1 h timelag woody fuel and from 50% to 100% in 10 h timelag fuel load. These reductions by fuel categories were established by burn season (April) according to the differences between early season and late season burns (Knapp et al., 2005). The objectives were achieved by prescribed fires with the following "burn window": last precipitation (>1 mm) between 4 and 12 days before, temperature range from 16 °C to 26 °C, relative humidity between 38.5% and 65% and maximum mean wind speed varied on 5–12 km/h (inside of the forest with drag friction considered). With temperature lower than 20 °C and relative humidity above 50%, it was necessary to burn at least 9 days after the last precipitation to get the reduction targets. The most efficient condition of the litter moisture ranged from 9% to 15% for surface litter and from 23% to 40% for partly decomposed litter. The fuel compaction also takes part in getting the targets under the recommended "burn window". If a high woody compacted fuel (as an example "PR2") existed, the efficient fuel reduction would need lower decomposed litter moisture and flame length upper than 1 m. These accumulations are usually distributed in small or isolated patches and they are not considered in general prescribed fire planning. To sum up, our results show that prescribed fires after biomass harvesting treatments can be a valuable tool to reduce fire hazards according to the goals were identified by forest managers (McCaw, 2013).

Table 6
Fuel reduction estimations based on burning results.

Model form	a	b	c	R^2
TR = a ∗ Md^2 + b ∗ Md + c	0.086	−7.096	205.399	0.957**
TR = a + b/Md	26.028	1369.623	–	0.892**
TR = a + b ∗ Md + c ∗ v	121.445	−1.317	−4.007	0.936**
DR = a + b ∗ SR	−230.695	2.837	–	0.916**
1hFR = a ∗ Md^2 + b ∗ Md + c	−0.156	8.835	−36.667	0.912**
10hFR = a ∗ Md^2 + b ∗ Md + c	−0.025	1.632	43.876	0.857*

Where "TR" is the total fuel reduction (%), "Md" is the partly decomposed litter moisture (%), "v" is the spread rate (m/min), "DR" is the partly decomposed litter reduction (%), "SR" is the surface litter reduction (%), "1hFR" is the 1 h timelag fuel reduction (%) and "10hFR" is the 10 h timelag fuel reduction (%).
** $p < 0.05$.
* $p < 0.1$.

5. Conclusions

An adequate management of prescribed fires requires the knowledge of the main environmental and fuel variables, which influence on fire behavior, in an efficient way to achieve the established targets. Prescribed fires on biomass harvesting scenarios could fulfill a meaningful fire prevention function based on fuel consumption and economic efficiency criteria. It is important to optimize fuel reduction programs while ensuring ecological sustainability of ecosystems. In this sense, spring burns are feasible only if an important percentage of decomposition litter is respected to prevent soil erosion.

There is a growing rural importance on biomass resource in spite of the woody debris accumulation associated with mechanical harvesting. Therefore, an approach to value the prescribed fires effects, after biomass harvesting treatments, would be a useful planning tool for comprehensive management of the territory, mainly in forest fires prevention. Expressing the recommendations in terms of the "burn window" responds to a needed objectivity and simplicity required by the forest managers. This research provides decision markers a relatively easy tool to evaluate when to invest the fire resources available. In this sense, it aids managers in developing prescribed fires in a sustainability and efficient way to reduce damages to rural areas at risk.

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